♣EPA Ground Water Issue

Design Guidelines for Conventional Pump-and-Treat Systems

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The RCRA/Superfund Ground-Water Forum is a group of scientists representing EPA's Regional Superfund Offices, committed to the identification and resolution of ground-water issues affecting the remediation of Superfund sites. Design of conventional ground-water extraction and injection (i.e., pump-and-treat) systems has been identified by the Forum as an issue of concern to decision makers. This issue paper focuses on design of conventional ground-water extraction and injection systems used in subsurface remediation.

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Introduction

Containment and cleanup of contaminated ground water are among the primary objectives of the CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act; also known as Superfund) and RCRA (Resource Conservation and Recovery Act) remediation programs. Ground-water contamination problems are pervasive in both programs; over 85 percent of CERCLA National Priority List sites and a substantial portion of RCRA facilities have some degree of ground-water contamination (U.S. EPA, 1993a). A common approach to deal with contaminated ground water is to extract the contaminated water and treat it at the surface prior to discharge or reinjection as illustrated in Figure 1. This is referred to as conventional pump-and-treat (P&T) remediation.

Conventional pump-and-treat is an applicable component of many remedial systems. However, such a system will not be appropriate to achieve restoration in portions of many sites due to hydrogeologic and contaminant-related limitations such as those presented by significant accumulations of DNAPLs (denser-than-water nonaqueous phase liquids) trapped below the water table. Such limitations will directly impact the effectiveness of P&T at many sites and the selection of remedial actions. Detailed discussion of the contaminant transport and fate processes that limit the potential for subsurface restoration using P&T and their characterization is beyond the scope of this document.
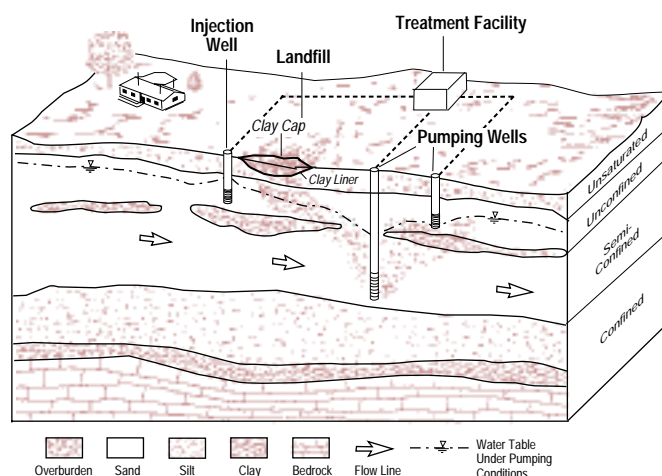

Figure 1. Example of a P&T system (after Mercer et al., 1990).

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Inadequate design and implementation also may severely impact the performance of a P&T system. Examples of design inadequacies include too few recovery wells, insufficient pumping rates, deficient well locations or completion intervals, and failure to account for complex chemistry of contaminants. Similarly, poor system operation, exemplified by excessive downtime or failure to manipulate pumping schemes to limit ground-water stagnation, will restrict P&T effectiveness. This document provides guidance on designing conventional ground-water P&T systems. Chemical enhancements to P&T and immiscible contaminant recovery methods are addressed elsewhere (e.g., American Petroleum Institute, 1989, 1992; Palmer and Fish, 1992; U.S. EPA, 1992a, 1995; Grubb and Sitar, 1994; NRC, 1994).

P&T Remediation Strategies

In order to determine an appropriate strategy to manage contaminated ground water, it is necessary first to evaluate site conditions and define remediation goals. Historically, the goal of ground-water remediation has been to protect human health and the environment and to restore ground water to beneficial uses where practicable. For ground water that is or may be used for drinking, clean-up goals under CERCLA and RCRA generally are set at drinking water standards such as Maximum Contaminant Levels (MCLs) established under the Safe Drinking Water Act. Other clean-up requirements may be appropriate for ground water that is not used for drinking.

It has long been recognized that chemical transport from contaminant source/release areas, such as abandoned landfills and leaking tanks, contaminates ground water and other media in downgradient areas (e.g., OTA, 1984). As such, a common strategy for managing contaminated ground water has been to remove or contain contaminant sources (e.g., by excavation, construction of physical barriers, and/or pumping) and to address downgradient contamination using P&T technology.

Strategies for managing ground-water contamination (Figure 2) using P&T technology include: (1) hydraulic/physical containment, (2) ground-water quality restoration, and (3) mixed objective strategies. Several innovative technologies, such as air sparging, engineered bioremediation, and permeable treatment walls, can be used in conjunction with P&T, or alone, to address these ground-water remediation objectives. At some sites, natural attenuation processes may limit the need for P&T. The management strategy selected depends on site-specific hydrogeologic and contaminant conditions, and remediation goals.

Hydraulic Containment

P&T systems are frequently designed to hydraulically control the movement of contaminated ground water in order to prevent continued expansion of the contamination zone. At sites where the contaminant source cannot be removed (e.g., a landfill or bedrock with DNAPLs), hydraulic containment is an option to achieve source control. Hydraulic containment of dissolved contaminants by pumping ground water from wells or drains has been demonstrated at numerous sites. The concept is illustrated in Figure 3. Properly controlled fluid injection using wells, drains, or surface application (e.g., along the downgradient periphery of the proposed containment area) and physical containment options (e.g., subsurface barrier walls and surface covers to limit inflow) can enhance hydraulic containment
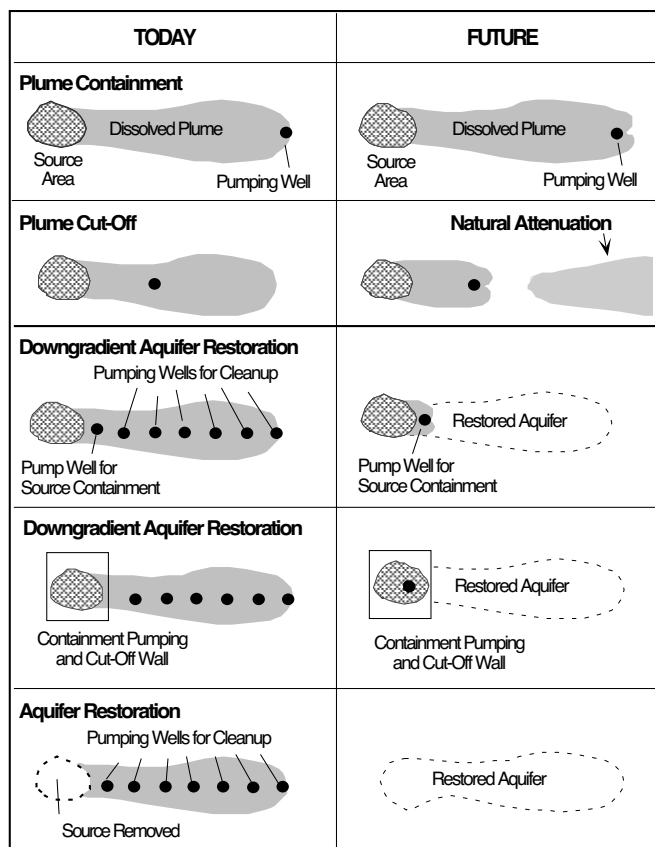
Figure 2. *Several ground-water contamination management strategies using P&T technology (after NRC, 1994; Cherry et al., 1992).*

systems by reducing the pumping rate required to maintain containment. In many cases, hydraulic containment systems are designed to provide long-term containment of contaminated ground water or source areas at the lowest cost by optimizing well, drain, surface cover, and/or cutoff wall locations and by minimizing pumping rates.

Cleanup/Restoration

For sites where the contaminant source has been removed or contained, it may be possible to clean up the dissolved plume. P&T technology designed for aquifer restoration generally combines hydraulic containment with more aggressive manipulation of ground water (i.e., higher pumping rates) to attain clean-up goals during a finite period. Ground-water cleanup is typically much more difficult to achieve than hydraulic containment. Hydrogeologic and contaminant conditions favorable to cleanup (e.g., degradable dissolved contaminants in uniform, permeable media) are summarized in Figure 4.

Mixed Objective Strategies

At many sites, P&T systems can be used to contain contaminant source areas and attempt restoration of downgradient dissolved plumes (Figure 2). A mixed P&T strategy is appropriate, therefore, at sites where different portions of the contaminated
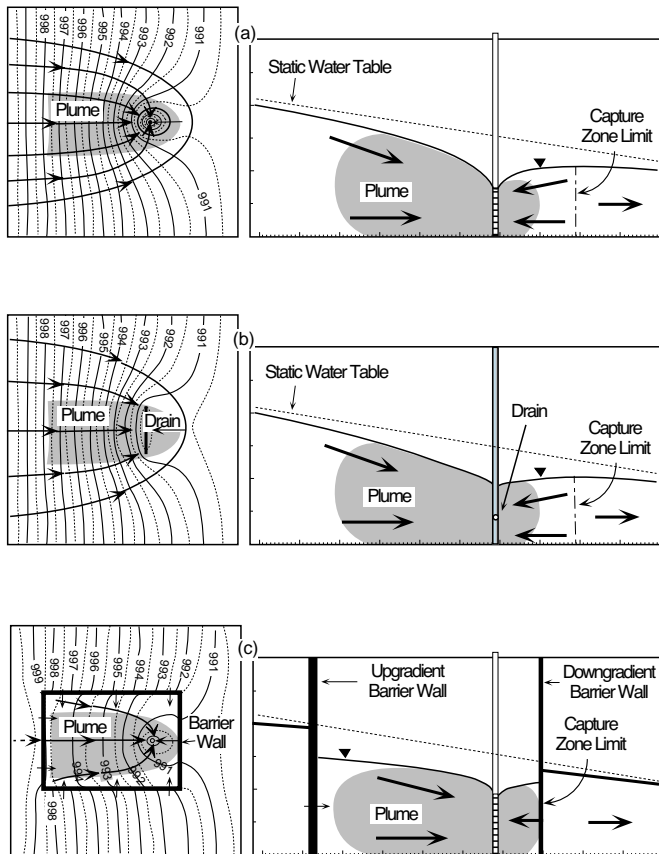
Figure 3. *Examples of hydraulic containment in plan view and cross section using an extraction well (a), a drain (b), and a well within a barrier wall (c).*

region are amenable to remediation using different methods. At sites contaminated with LNAPLs (lighter-than-water NAPLs), for example, a mixed remedial strategy may include: (1) vacuum-enhanced pumping to recover free product, affect hydraulic containment, and stimulate bioremediation in the LNAPL release area; and (2) restoring downgradient ground water via natural attenuation, P&T, and/or air sparging.

Characterizing Sites for P&T Design

The main goal of site characterization should be to obtain sufficient data to select and design a remedy (NRC, 1994). This is accomplished by investigating: (1) the nature, extent, and distribution of contaminants in source areas and downgradient plumes; (2) potential receptors and risks posed by contaminated ground water; and (3) hydrogeologic and contaminant properties that affect containment, restoration, and system design in different site areas. Categories of data used to formulate a site conceptual model for remedy evaluation are identified in Figure 5. The conceptual model is used to formulate remedial strategies such as restoration and/or containment.

Inadequate site characterization can lead to flawed P&T design and poor system performance. A complete understanding of a contamination site is unobtainable, however, due to subsurface complexities and investigation cost. Thus, characterization

efforts must develop sufficient data to select and design an effective remedy while recognizing that significant uncertainties about subsurface conditions will persist.

Site characterization for remedial design is an extensive subject, key aspects of which are addressed briefly below. Additional information regarding procedures and strategies for investigating contamination sites is provided by U.S. EPA (1988a, 1991a, 1993b), Nielsen (1991), Cohen and Mercer (1993), Sara (1994), CCME (1994), and Boulding (1995).
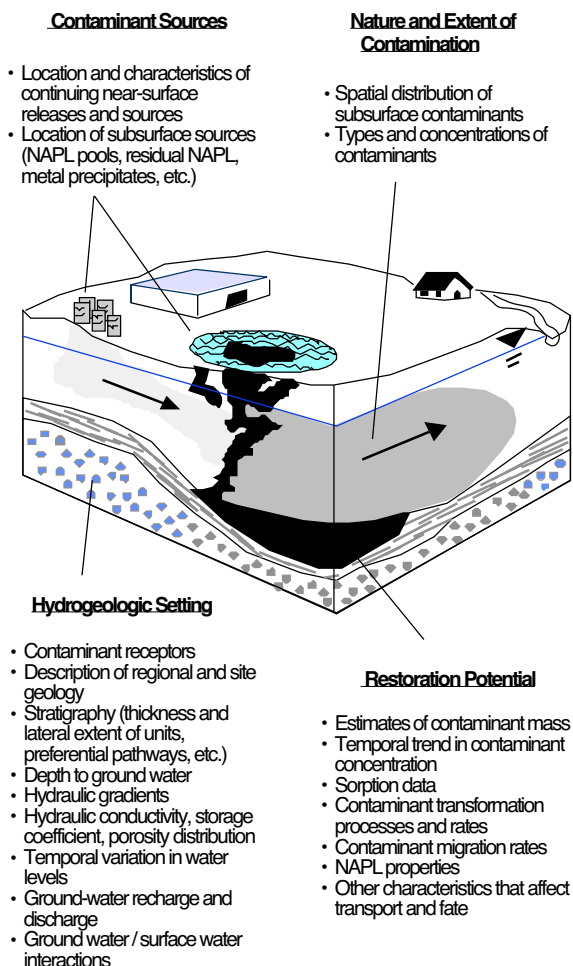
Using a Phased and Integrated Approach

Due to slow contaminant transport and interphase transfer, many P&T systems will operate for decades to contain and clean up contaminated ground water. Data collected during investigation and remediation should be reviewed periodically to refine the site conceptual model and identify modifications that will improve P&T system performance. Thus, as depicted in Figure 6, a phased and integrated approach should be taken to site characterization and remediation. For example, given significant uncertainty regarding well locations and pumping rates needed to achieve remedial objectives, it may be prudent to initiate pumping at several locations and then determine system expansion requirements based on performance monitoring data. This phased approach to system installation may be more cost effective than grossly overdesigning the system to account for uncertainty in subsurface characterization at many sites.

During the initial phase of site investigation, prior studies and background information are reviewed to identify likely

CONTAMINANT AND HYDROGEOLOGIC CHARACTERISTICS	GENERALIZED RESTORATION DIFFICULTY SCALE — Increasing Difficulty —→	
SITE USE		
Nature of Release	Small volume Short duration —→ Slug release	Large volume Long duration Continual
CONTAMINANT PROPERTIES		
Biotic/Abiotic Decay Potential	High ——→	Low
Volatility	High ——→	Low
Contaminant Sorption Potential	Low ——→	High
CONTAMINANT DISTRIBUTION		
Contaminant Phase	Aqueous, Gaseous —→ LNAPL —→ DNAPL	
Volume of Contaminated Media	Small ——→	Large
Contaminant Depth	Shallow ——→	Deep
GEOLOGIC CONDITIONS		
Stratigraphy	Simple ——→	Complex
Unconsolidated Media Texture	Coarse-grained —→	Fine-grained
Degree of Heterogeneity	Low ——→	High
GROUNDWATER FLOW PARAMETERS		
Hydraulic Conductivity	High ——→ (> 0.01 cm/s)	Low (< 0.0001 cm/s)
Temporal Variation	Little ——→	High
Vertical Flow	Little ——→	High downward

Figure 4. *Generalized ground-water restoration difficulty scale (modified from U.S. EPA, 1993a).*

Contaminant Sources

- Location and characteristics of continuing near-surface releases and sources
- Location of subsurface sources (NAPL pools, residual NAPL, metal precipitates, etc.)

Nature and Extent of Contamination

- Spatial distribution of subsurface contaminants
- Types and concentrations of contaminants

Hydrogeologic Setting

- Contaminant receptors
- Description of regional and site geology
- Stratigraphy (thickness and lateral extent of units, preferential pathways, etc.)
- Depth to ground water
- Hydraulic gradients
- Hydraulic conductivity, storage coefficient, porosity distribution
- Temporal variation in water levels
- Ground-water recharge and discharge
- Ground water / surface water interactions

Restoration Potential

- Estimates of contaminant mass
- Temporal trend in contaminant concentration
- Sorption data
- Contaminant transformation processes and rates
- Contaminant migration rates
- NAPL properties
- Other characteristics that affect transport and fate

Figure 5. *Types of data used to develop a site conceptual model for remedy assessment (modified from U.S. EPA, 1993a).*
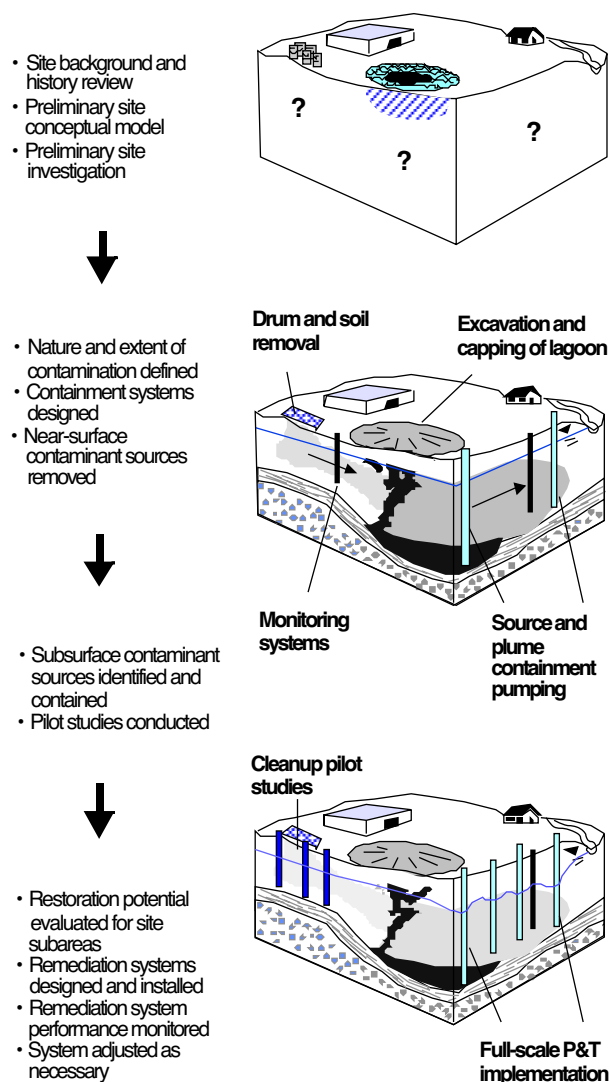
contaminant sources, transport pathways, and receptors. Based on this initial conceptualization, a data collection program is devised to better define the nature and extent of contamination and provide information (i.e., hydraulic conductivity distribution, aquifer boundary conditions, and initial hydraulic gradients) for remedy design. Contaminant source and downgradient dissolved plume areas should be delineated early during the characterization process to clarify site management strategies. P&T systems can often be designed to contain source and downgradient plume areas based on data acquired during the early and intermediate phases of investigation. Additional studies, including monitoring of actual P&T performance, are usually required, however, to assess the potential to restore ground-water quality in different site areas.

Mathematical models representing aspects of the site conceptual model should be used to evaluate alternative extraction/injection schemes, perform sensitivity analysis, and identify additional data needs. Integrating P&T operation and monitoring data can lead to model refinements and design enhancements.

P&T performance is typically assessed by measuring hydraulic heads and gradients, ground-water flow directions and rates,

pumping rates, pumped water and treatment system effluent quality, and contaminant distributions in ground water and porous media. Guidance on methods for monitoring P&T performance is provided by Cohen et al. (1994). Careful examination of system performance, considering transient effects, is commonly warranted during the first months after start-up, and after subsequent major changes to P&T operation. Remediation, therefore, should be considered part of site characterization, yielding data that may lead to improved P&T system design and operation.

In recognition of inherent uncertainty and the potential for phased remediation, a reasonable degree of flexibility should be incorporated in P&T design to accommodate modifications. This may involve overdesign of certain system components (e.g., pipe or electric wire size), use of modular equipment (e.g., package treatment units), and strategic placement of junction boxes. Overdesign may allow system modifications such as

- Site background and history review
- Preliminary site conceptual model
- Preliminary site investigation

- Nature and extent of contamination defined
- Containment systems designed
- Near-surface contaminant sources removed

Drum and soil removal

Excavation and capping of lagoon

- Subsurface contaminant sources identified and contained
- Pilot studies conducted

Monitoring systems

Source and plume containment pumping

Cleanup pilot studies

- Restoration potential evaluated for site subareas
- Remediation systems designed and installed
- Remediation system performance monitored
- System adjusted as necessary

Full-scale P&T implementation

Figure 6. *Iterative phases of site characterization and remediation (modified from U.S. EPA, 1993a; NRC, 1994).*

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incorporation of additional extraction wells or higher flow rates at relatively minimal expense. The degree of overdesign required as a contingency for uncertainties in subsurface conditions will be site specific and largely dependent on the level of site characterization performed prior to design. Estimates of potential ranges of required flowrates may be obtained at many sites during design-stage ground-water flow modeling.
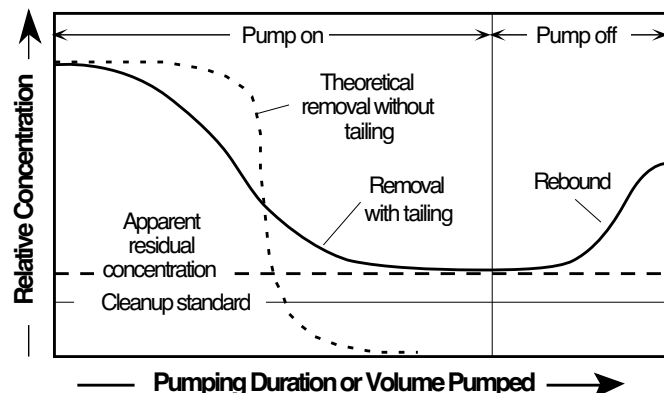
Contaminant Characterization

Contaminant characterization is a key element of remedial evaluations. The nature, distribution, and extent of contamination will influence the selection of remedial actions and specific system designs. Contaminant characterization data needed to select and design a P&T system are listed in Figure 5. Important goals include: (1) delineating contaminant source areas and release characteristics; (2) defining the nature and extent (horizontal and vertical) of contamination; (3) characterizing contaminant transport pathways, processes, and rates; (4) estimating risks associated with contaminant transport; and (5) assessing aquifer restoration potential (see below). Contaminant characterization efforts generally involve document review, indirect and direct field characterization methods (e.g., soil, soil gas analysis and ground-water sampling), and data analysis.
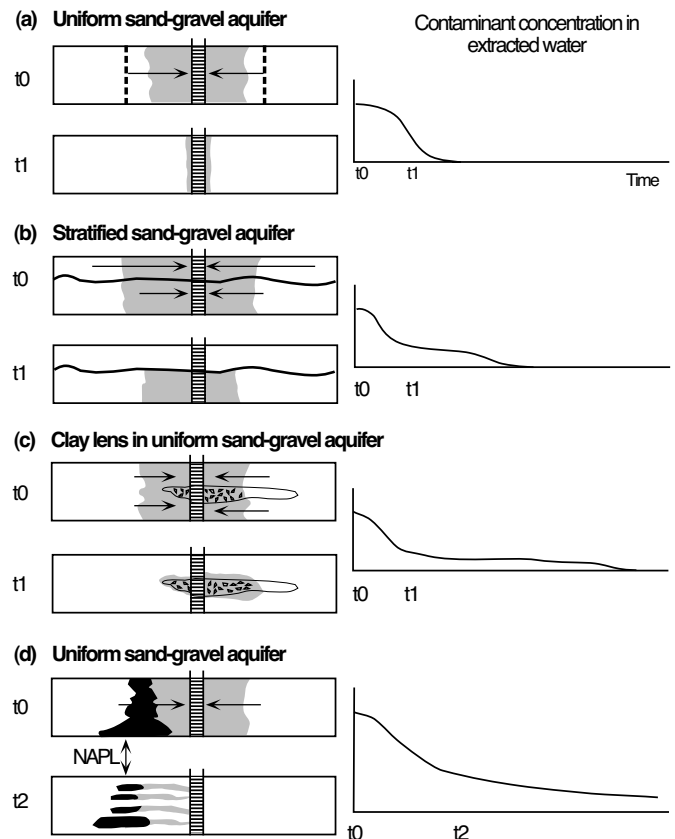
Assessing Potential Limitations to P&T

Monitoring contaminant concentrations in ground water with time at P&T sites often reveals "tailing" and "rebound" phenomena. "Tailing" refers to the progressively slower rate of dissolved contaminant concentration decline observed with continued operation of a P&T system (Figures 7 and 8). The tailing contaminant concentration may exceed clean-up standards. Another problem is that dissolved contaminant concentrations may "rebound" if pumping is discontinued after temporarily attaining a clean-up standard (Figure 7).

If aquifer restoration is a potential remediation goal, then site characterization should investigate the physical and chemical phenomena that cause tailing and rebound. At many sites, most of the contaminant mass is not dissolved in ground water, but is present as NAPL, adsorbed species, and solids. Slow mass transfer of contaminants from these phases to ground water

Figure 8. *Hypothetical examples of contaminant removal using P&T (modified from Mackay and Cherry, 1989). Black indicates NAPL; stippling indicates contaminant in dissolved and sorbed phases (with uniform initial distribution); and arrows indicate relative ground-water velocity. Ground water is pumped from the well at the same rate for each case. The dotted lines in (a) represent the volume of water that would have to be pumped to flush slightly retarded contaminants from the uniform aquifer.*

during P&T will cause tailing and prolong the clean-up effort. Physical causes of tailing include ground-water velocity and flowpath variations, and the slow diffusion of contaminants from low permeability zones during P&T operation. These phenomena are briefly discussed in Appendix A.

Tailing and rebound patterns associated with different physical and chemical processes are similar. Multiple processes (i.e., dissolution, diffusion, and desorption) will typically be active at a P&T site. Diagnosis of the cause of tailing and rebound, therefore, requires careful consideration of site conditions and usually cannot be made by examining concentration-versus-time data alone. Quantitative development of the conceptual model using analytical or numerical methods may help estimate the relative significance of different processes that cause tailing and rebound. Knowledge of the potential limitations at each site may allow more detailed analyses of the potential effectiveness of different P&T remediation strategies and different system configurations.

Figure 7. *Concentration versus pumping duration or volume showing tailing and rebound effects (modified from Keely, 1989).*

Hydrogeologic Characterization

Components of hydrogeologic investigation needed for P&T design are listed in Figure 5. Care must be taken to avoid exacerbating the contamination problem as a result of field work (e.g., inducing unwanted migration via drilling or pumping), or performing investigations not needed for risk or remedy assessment. Characterizing ground-water flow and contaminant transport is particularly challenging in heterogeneous media, especially where contaminants have migrated into fractured rock. Methods for characterizing fractured rock settings include drilling/coring, aquifer tests, packer tests, tracer tests, surface and borehole geophysical surveys, borehole flowmeter surveys, and air photograph fracture trace analysis (Sara, 1994). At the scale of many contaminated sites, complete characterization of fractured rock (and other heterogeneous media) may be economically infeasible (Schmelling and Ross, 1989), and not needed to design an effective P&T system (NRC, 1994). The appropriate characterization methods and level-of-effort must be determined on a site-specific basis.

Long-term aquifer tests and phased-system installations are often cost-effective means for acquiring field-scale hydrogeologic and remedial design data. Aquifer tests should be conducted to acquire field-scale measurements of hydrogeologic properties, such as formation transmissivity and storage coefficient, that are critical to extraction system design. Test results are used to: (1) determine well pumping rates and drawdowns; (2) assess well locations and pumping rates needed for full-scale operation; (3) evaluate the design of well and treatment system components; and (4) estimate capital and O&M costs. Recommended procedures for conducting aquifer tests are described by Osborne (1993) and others.

The number and duration of tests required to obtain sufficient data to design a P&T system depends on many factors, including plume size, the distribution of hydrogeologic units, their hydraulic properties, and hydrogeologic boundary conditions. In general, multiple tests are warranted at large and heterogeneous sites. Test design parameters (including specification of observation well locations, test duration, and pumping rate) can be assessed using well hydraulics solutions, ground-water flow models, and/ or by conducting short-term step tests.

Observation wells should be located close enough to the pumping well to ensure adequate responses to pumping stress. Drawdowns will depend on site-specific hydrologic conditions that influence ground-water elevations during the test. Wells should also be located so that data may be used to evaluate heterogeneity and anisotropy, if warranted.

Although reasonable estimates of formation transmissivity can generally be obtained using data acquired during the first several hours of pumping (if observation wells are close to the pumping well), it may be advisable to extend aquifer tests to days or weeks to evaluate capture zones, boundary conditions, and ground-water treatability issues. Slug tests can also be used to augment aquifer test results. However, short-term aquifer and slug tests generally are not as reliable indicators of system performance as long-term aquifer tests.

Disposal options for aquifer test water are subject to site conditions and regulations but may include: discharge to a storm or sanitary sewer, discharge to the ground, discharge to surface water, reinjection to the subsurface, and transport to an off-site disposal facility. Regulatory agencies should be contacted to determine disposal requirements.

Ground-Water Treatability Studies

Treatability data needed for design of ground-water treatment systems generally should be acquired by conducting chemical analyses and treatability studies on contaminated ground water extracted during aquifer tests. Analysis of water samples obtained at different times during an aquifer test often will provide data regarding the initial range of contaminant concentrations in influent water to the treatment plant. Bench- and pilot-scale treatability studies are valuable means for determining the feasibility of candidate processes for treating contaminated ground water (U.S. EPA, 1989, 1994a). Laboratory bench-scale tests use small quantities of extracted ground water to provide preliminary data on various treatment processes, pretreatment requirements, and potential costs. During pilot-scale tests, skid-mounted or mobile pilot equipment is operated to study the effect of varying system parameters (e.g., flow rate) on treatment results and to identify potential problems, such as chemical precipitation of dissolved iron (Fe) and manganese (Mn) in an air stripper.

Air stripping and granular activated carbon (GAC) units may be used to remove organic compounds from ground water during aquifer tests; ion exchange/adsorption can be used to remove most metals (U.S. EPA, 1996). Air stripping is generally more cost-effective than GAC for treating volatile organic compounds when flow rates exceed 3 gpm (Long, 1993), but may require additional vapor phase treatment.

Potential for Fluid Injection

Artificial fluid injection/recharge is used to enhance hydraulic control and flushing of contamination zones. Treatment plant effluent or public supply water can be injected above or below the water table via wells, trenches, drains, or surface application (sprinkler, furrow, or basin infiltration). The applied water can be amended to stimulate bioremediation or to minimize well and formation clogging problems. Recharge is typically controlled by maintaining the water level in injection wells or drains or by pumping at specified rates. Regulatory agencies should be contacted to determine injection permit requirements. Potential problems with the use of injection include undesired horizontal or vertical contaminant migration due to the increased hydraulic gradients. Sites where injection is to be used should be carefully characterized and monitored to ensure that environmental problems are not exacerbated.

Aspects of site characterization critical to fluid injection design include determination of: (1) site stratigraphy and permeability distribution, (2) hydrogeologic boundary conditions, (3) possible injection rates and resulting hydraulic head and ground-water flow patterns, and (4) the potential for well and formation clogging due to injection.

Hydraulic parameters estimated from analysis of standard aquifer tests are often used to design injection systems. Constant-head, constant-rate, and stepped rate or head injection tests can also be conducted to evaluate hydraulic properties and injection potential using standard aquifer test procedures (Driscoll, 1986; Kruseman and deRidder, 1990). More discrete

techniques (e.g., packer tests, borehole flowmeter surveys) may be desirable to identify high permeability zones. Hydraulic heads and ground-water flow patterns resulting from injection can be examined and predicted using well or drain hydraulics equations and ground-water flow models. Such analysis can also be used to determine potential injection rates, durations, and monitoring locations for injection tests. In addition to helping estimate formation hydraulic properties, injection tests provide information on water compatibility and clogging issues that are critical to injection design.

The most common problem associated with fluid injection is permeability reduction due to clogging of screen openings. This causes a decline in injection rates. Clogging results from physical filtration of solids suspended in injected water, chemical precipitation of dissolved solids, and the excessive growth of microorganisms (also known as biofouling). Less frequently, well or formation damage results from air entrainment, clay swelling, and clay dispersion due to injection. In general, the injection capacity of a system is often overdesigned by a significant factor (e.g., 1.5 to 2) to account for loss of capacity under operating conditions due to such problems as permeability reduction and the temporary loss of capacity during well maintenance. The optimal degree of overdesign is site specific and will depend on such factors as the rate at which clogging occurs and the cost of maintenance.

The potential for well clogging and mitigative measures can be examined by analysis of the injected fluid and bench scale testing. In general, injection water should contain: (1) no suspended solids to minimize clogging; (2) little or no dissolved oxygen, nutrients, and microbes to minimize biofouling; and (3) low concentrations of constituents that are sensitive to changes in pH, redox, pressure, and temperature conditions (e.g., Fe and Mn) to minimize precipitation. Column permeameter tests can be conducted to examine changes in hydraulic conductivity resulting from injection. Due to the potential significance of many hydrogeologic, physical, and chemical factors, however, fluid injection is best evaluated by conducting extended injection tests during which injection rates and hydraulic heads are monitored carefully. Results of field tests help define formation hydraulic properties, potential injection rates, injection well spacings, mounding response, and clogging potential.

Dissolved or suspended solids may need to be removed from water by aeration, flocculation, and filtration prior to injection. Similarly, nutrients and/or dissolved oxygen may need to be removed to prevent biofouling. Water should be injected below the water table through a pipe to prevent its aeration in the well. Injecting warm water can also promote biofouling. Clogging problems can be minimized by overdesigning injection capacity (e.g., by installing more wells, longer screens, etc.) and implementing a regular well maintenance program.

Extraction and injection rate monitoring and well inspection, using a downhole video camera or other means, can help identify wells in need of treatment or replacement. Periodic rehabilitation of wells or drains (by surging, jetting, chlorination, or acid treatment) may be required to restore declining injection rates (Driscoll, 1986). Chemical incrustation can be addressed by acid treatment, backwashing, mechanical agitation (with a wire brush or surge block), and pumping. Strong oxidizing agents, such as a chlorine solution, can be used in conjunction with backwashing, mechanical agitation, and pumping to treat wells damaged by slime-producing bacteria. Acidification and chlorination, however, may interfere with interpretation of ground-water chemistry data. Fine particles can be removed (to some extent) using standard well development techniques. Experienced well drillers should be contacted for advice on rehabilitation methods. These potential problems need to be considered when projecting P&T costs. Significant maintenance may be required at many sites to retain desired injection capacity. More detailed discussions of the engineering aspects of water injection are provided by Pyne (1995).

Data Presentation

Complete discussion of methods for characterization and remedial design analyses and supporting data is beyond the scope of this document. In general, such information should be presented graphically and accompanied by supporting calculations and analyses. Tools for electronic storage, manipulation, analysis, and display of data and designs are generally available and often provide a convenient format for storage and access of this information (e.g., database, CAD, and/or GIS programs). Characterization data such as three-dimensional contaminant distribution are best presented on site maps and in representative cross sections. Hydraulic properties and hydraulic head data may also be presented in similar fashion. Pertinent features such as well locations (i.e., monitoring, production, injection), surface water bodies, potential source areas, and relevant structures should be included, as appropriate. Supporting data should be provided in tabular or spreadsheet form and accompany the maps and cross sections.

Capture Zone Analysis for P&T Design

P&T design is refined by performing field tests, modeling alternative injection/extraction schemes, and monitoring system performance. The first step in establishing design criteria, after characterizing pre-remedy ground-water flow patterns and contaminant distributions, is to determine the desired containment and/or restoration area (two-dimensional) and volume (three-dimensional). These should be clearly specified in the remedial design and monitoring plans. After defining the proposed containment area, a capture zone analysis is conducted to design the P&T system and a performance monitoring plan is developed based on the predicted flow field.

The capture zone of an extraction well or drain refers to that portion of the subsurface containing ground water that will ultimately discharge to the well or drain (Figures 3 and 9). It should be noticed that the capture zone of a well is not coincident with its drawdown zone of influence (ZOI) (Figure 9). The extent of the ZOI depends largely on transmissivity and pumping rate under steady-state conditions. However, the shape of the capture zone depends on the natural hydraulic gradient as well as pumping rate and transmissivity. Relatively high natural hydraulic gradients result in narrow capture zones that do not extend far in the downgradient direction. Therefore, some sidegradient and downgradient areas within the ZOI of a recovery well will be beyond its capture zone, and "rules-of-thumb" regarding overlapping drawdown zones should not be used to determine well spacings or pumping rates for P&T design.

In recent years, many mathematical models have been developed or applied to compute capture zones, ground-water pathlines, flushing rates, and associated travel times to extraction
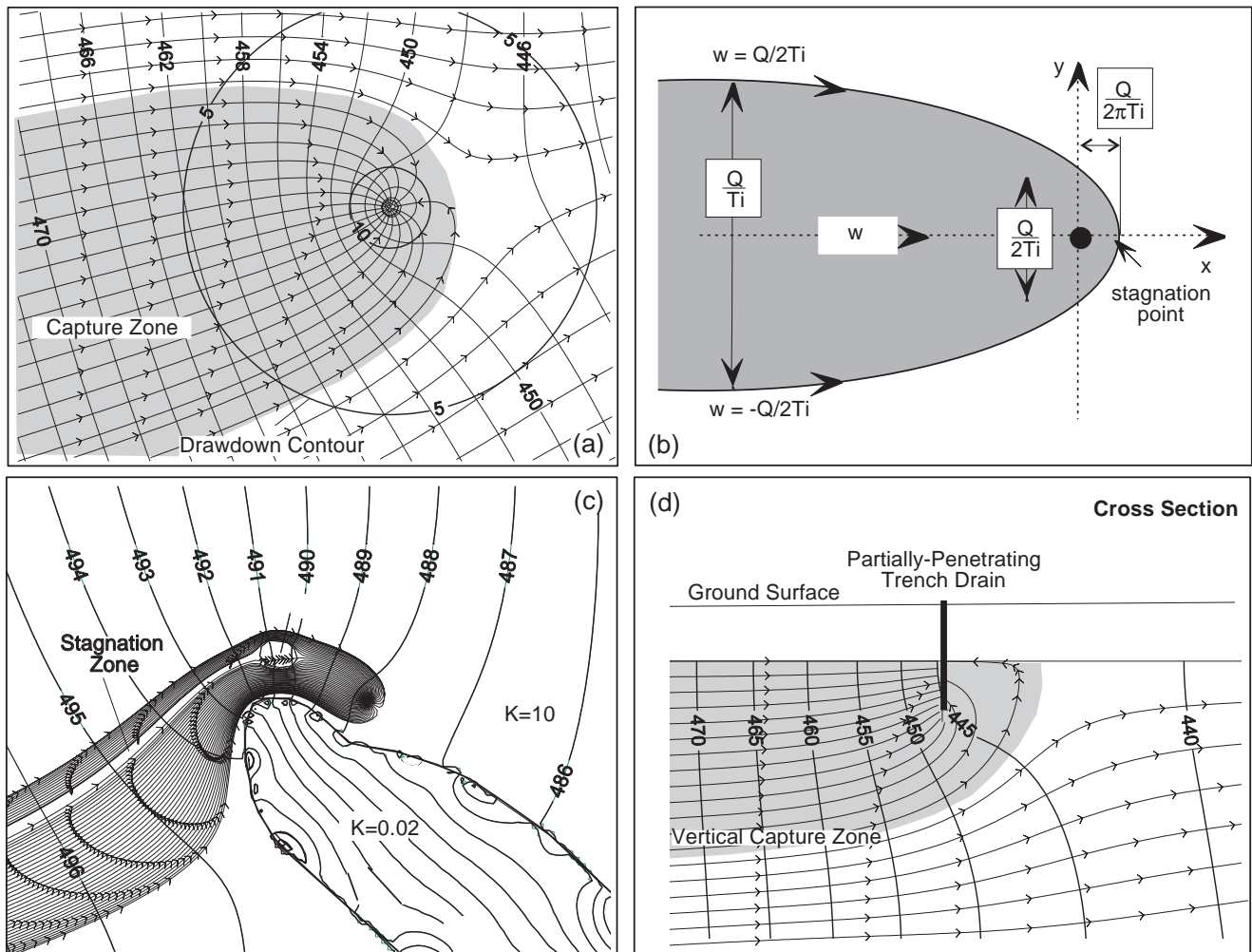
Figure 9. *(a) Illustration of drawdown contours (i.e., zone of influence) and the capture zone of a single pumping well in a uniform medium. Equations for the dividing streamlines (w = Q/2Ti) that separate the capture zone of a single well from the rest of an isotropic, confined aquifer with a uniform regional hydraulic gradient are given in (b) where T = transmissivity, Q = pumping rate, and i = initial uniform hydraulic gradient. Simplified capture zone analysis methods may provide misleading results when applied to more complex problems, such as those dealing with heterogeneous media, as depicted in (c) where K = relative hydraulic conductivity, and three-dimensional flow (d).*

wells or drains (Javandel et al., 1984; Javandel and Tsang, 1986; Shafer, 1987a,b; Newsom and Wilson, 1988; Fitts, 1989,1994; Strack, 1989; Bonn and Rounds, 1990; Bair et al., 1991; Rumbaugh, 1991; Bair and Roadcap, 1992; Blandford et al., 1993; Gorelick et al., 1993; Pollock, 1994; Strack et al., 1994). These models provide insight into flow patterns generated by alternative P&T schemes and the selection of monitoring locations and frequency. Additionally, linear programming methods are being used to optimize P&T design (Ahlfeld and Sawyer, 1990; Gorelick et al., 1993; Hagemeyer et al., 1993) by specifying an objective function subject to various constraints (e.g., minimize pumping rates but maintain inward hydraulic gradients).

Model selection for P&T design analysis depends on the complexity of the site, available data, and the familiarity of the analyst with different codes. In general, the simplest tool applicable to site conditions and the desired degree of uncertainty should be used in design. However, conditions at many sites will be sufficiently complex that screening level characterizations and design tools will result in significant uncertainty. Regardless of the design tools which are used, capture zone analysis should also be conducted, and well locations and pumping rates optimized, by monitoring hydraulic heads and flow rates during aquifer tests and system operation. Conceptual model refinements gained by monitoring lead to enhanced P&T design and operation. In some cases, these refinements are incorporated in a mathematical model that is used to reevaluate and improve system design.

Capture Zone Analysis Tools

Many types of tools are available for capture zone analysis and system design (Table 1). Graphical methods are useful screening level design tools in many situations. Based on this approach, the simple graphical method shown in Figure 9 can be used to locate the stagnation point and dividing streamlines, and then

Table 1.   P&T Design Tools (modified from van der Heijde and Elnawawy, 1993)

Method	Example	Description
Aquifer Tests and Pilot Testing		Controlled and monitored pilot tests are conducted to assist P&T design. Suggested operating procedures for aquifer tests and analytical methods are described by Osborne (1993) and many others. Test results should be used to improve P&T design modeling, where applicable.
Graphical - Capture Zone Type Curves	(Javandel and Tsang, 1986)	A simple graphical method can be used to determine minimum pumping rates and well spacings needed to maintain capture using 1, 2, or 3 pumping wells along a line perpendicular to the regional direction of ground-water flow in a confined aquifer.
Semi-analytical Ground-Water Flow and Pathline Models	WHPA (Blandford et al., 1993) WHAEM (Strack et al., 1994; Haitjema et al., 1994)	These models superposition analytic functions to simulate simple or complex aquifer conditions including wells, line sources, line sinks, recharge, and regional flow (Strack, 1989). Advantages include flexibility, ease of use, speed, accuracy, and no model grid. Generally limited to analysis of 2-D flow problems.
Numerical Models of Ground-Water Flow	MODFLOW (McDonald and Harbaugh, 1988)	Finite-difference (FD) and finite element (FE) ground-water flow models have been developed to simulate 2-D areal or cross-sectional and quasi- or fully- 3-D, steady or transient flow in anisotropic, heterogeneous, layered aquifer systems. These models can handle a variety of complex conditions allowing analysis of simple and complex ground-water flow problems, including P&T design analysis. Various pre- and post-processors are available. In general, more complex and detailed site characterization data are required for simulation of complex problems.
Pathline and Particle Tracking Post-Processors	MODPATH (Pollock, 1994) GPTRAC (Blandford et al., 1993)	These programs use particle tracking to calculate pathlines, capture zones, and travel times based on ground-water flow model output. Programs vary in assumptions and complexity of site conditions that may be simulated (e.g., 2-D or 3-D flow, heterogeneity, anisotropy).
Numerical Models of Ground-water Flow and Contaminant Transport	MT3D (Zheng, 1992) MOC (Konikow and Bredehoeft, 1989)	These models can be used to evaluate aquifer restoration issues such as changes in contaminant mass distribution with time due to P&T operation.
Optimization Models	MODMAN (Greenwald, 1993)	Optimization programs designed to link with ground-water flow models yield answers to questions such as: (1) where should pumping and injection wells be located, and (2) at what rate should water be extracted or injected at each well? The optimal solution maximizes or minimizes a user-defined objective function and satisfies all user-defined constraints. A typical objective may be to maximize the total pumping rate from all wells, while constraints might include upper and lower limits on heads, gradients, or pumping rates. A variety of objectives and constraints are available to the user, allowing many P&T issues to be considered.

Software is available from a variety of sources including the Center for Subsurface Modeling Support at the U.S. EPA's Robert S. Kerr Environmental Research Center in Ada, Oklahoma (405-436-8594).

sketch the capture zone of a single well in a uniform flow field. This analysis is extended by Javandel and Tsang (1986) to determine the minimum uniform pumping rates and well spacings needed to maintain a capture zone between two or three pumping wells along a line perpendicular to the regional direction of ground-water flow. Their capture zone design criteria and type curves can be used for capture zone analysis, but more efficient P&T systems can be designed with nonuniform pump well orientations, spacings, and extraction rates. The extent to which the results of these simple models represent actual conditions depends on the extent to which the assumptions vary from actual site conditions.

More complex tools are often necessary to optimize P&T design and reduce uncertainty. Several semianalytical models employ complex potential theory to calculate stream functions, potential functions, specific discharge distribution, and/or velocity distribution by superimposing the effects of multiple extraction/injection wells using the Thiem equation on an ambient uniform ground-water flow field in a two-dimensional, homogeneous, isotropic, confined, steady-state system (e.g., RESSQC, Blandford et al., 1993). Streamlines, flushing rates, and capture zones associated with irregular well spacings and variable pumping rates can be simulated by these models. Many of these models support reverse and forward particle tracking to trace capture zones and streamlines. For example, reverse particle tracking is implemented in RESSQC to derive steady-state capture zones by releasing particles from the stagnation point(s) of the system and tracking their advective pathlines in the reversed velocity field. Similarly, time-related captures zones (Figure 10) are obtained by tracing the reverse pathlines formed by particles released around each pumping well (Shafer, 1987a; Blandford et al., 1993).

Application of semianalytical models to field problems requires careful evaluation of their limiting assumptions (e.g., isotropic and homogeneous hydraulic conductivity, fully-penetrating wells, no recharge, no vertical flow component, and constant transmissivity). Several analytical models relax these restrictive assumptions by superposition of various functions to treat recharge, layering, heterogeneity, three-dimensional flow, etc. Examples of two-dimensional time-related capture zones determined using TWODAN (Fitts, 1994; 1995) are shown in Figure 10. Given their ease of use and inherent uncertainties regarding the ground-water flow field, the more robust semianalytical models are ideal tools for evaluating alternative injection/extraction well locations and pumping rates at many sites. Where field conditions do not conform sufficiently to model assumptions, the simulation results will be invalid.

Numerical models are generally used to simulate ground-water flow in complex three-dimensional hydrogeologic systems (e.g., MODFLOW, McDonald and Harbaugh, 1988; and SWIFT/486, Ward et al., 1993). For example, the benefits of using partially-penetrating recovery wells to minimize pumping rates and unnecessary vertical spreading of contaminants can be examined using a three-dimensional flow model. Numerical flow model output is processed using reverse or forward particle-tracking software such as MODPATH (Pollock, 1994), GWPATH (Shafer, 1987b), and PATH3D (Zheng, 1990) to assess pathlines and capture zones associated with P&T systems at sites that cannot be adequately modeled using simpler techniques. Solute transport models are primarily run to address aquifer restoration issues such as changes in contaminant mass distribution with time due to P&T operation.

Ground-water flow models can be coupled with linear programming optimization schemes to determine the most effective well placements and pumping rates for hydraulic containment. The optimal solution maximizes or minimizes a user-defined objective function subject to all user-defined constraints. In a P&T system, a typical objective function may be to minimize the pumping rate to reduce cost, while constraints may include specified inward gradients at key locations, and limits on drawdowns, pumping rates, and the number of pumping wells. Gorelick et al. (1993) present a review of the use of optimization techniques in combination with ground-water models for P&T system design. Available codes include AQMAN (Lefkoff and Gorelick, 1987), an optimization code that employs the Trescott et al. (1976) two-dimensional ground-water flow model, and MODMAN (Greenwald, 1993), which adds optimization capability to the three-dimensional USGS MODFLOW model (McDonald and Harbaugh, 1988). A case study of optimization code use to assist P&T design is given by Hagemeyer et al. (1993).

Techniques have been presented in the literature for combining nonlinear optimization methods with contaminant transport simulation models (Gorelick, 1983; Wagner and Gorelick, 1987; Ahlfeld et al., 1988). These techniques are intended to provide solutions to problems formulated in terms of predicted concentrations (e.g., minimize pumping such that TCE is below the required clean-up level within five years at target locations). However, such analysis requires the use of a solute transport model and solution of a relatively difficult nonlinear problem. As a result, computation effort is large and uncertainty in results is high compared to optimization based on ground-water flow. Nonlinear optimization methods using solute transport models have not yet been packaged into commercial software and have rarely been applied to ground-water contamination problems.

Extraction / Injection Scheme Design

For a successful hydraulic containment, contaminants moving with ground water in the desired containment zone must follow pathlines that are captured by the P&T system. An appropriate remedial objective might be to minimize the total cost required to maintain perpetual containment and satisfy regulatory requirements. Given this objective, installing low permeability barriers (Figure 3c) to reduce pumping rates might be cost-effective. At sites with an objective of contaminant mass removal (i.e., where the containment area size may be diminished or P&T discontinued if clean-up goals are met), a more complex cost-effectiveness trade-off exists between minimizing hydraulic containment costs and maximizing contaminant mass removal rates.

Unless natural attenuation mechanisms are being relied upon to limit plume migration, hydraulic containment is generally a prerequisite for aquifer restoration. Restoration P&T design will typically reflect a compromise among objectives that seek to: (1) reduce contaminant concentrations to clean-up standards, (2) maximize mass removal, (3) minimize clean-up time, and (4) minimize cost. Due to the limitations described in Appendix A, P&T for aquifer restoration requires a high degree of performance monitoring and management to identify problem areas and improve system design and operation.

Restoration P&T ground-water flow management involves optimizing well locations, depths, and injection/extraction rates to maintain an effective hydraulic sweep through the